Development of a Streamflow Model Incorporating Stochastic Daily Climate, Climate Change, and El Niño La Niña Effects

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Abstract

Integrated Mine Water Management (MWM) is essential in selecting the strategy and management for a mine. A MWM tool simulates the uncertainty of predicting future climate and models the response of hydrological processes. For a copper-gold porphyry mine in the high Cordillera de Los Andes, SRK Consulting Inc. (SRK) developed a tool incorporating stochastic daily precipitation, snowpack, runoff, and temperature, including corrections for climate change and El Niño La Niña effects, into a single model. This record drove a numerical hydrologic, lumped-basin-parameter runoff model, calibrated to the regional and local stream gauge records to produce streamflow under simulated climate conditions.

Keywords: Climate Simulation, Climate Change, ENSO Predictions, Hydrologic Modelling

Introduction

The project was a Cu-Au porphyric intrusive mining project located in the Cordillera de Los Andes being consider for an open pit mine. Located near the continental divide of the Andes, the project watershed was divided into several sub-basins that corresponded to stream gauges recently installed by the project team, with areas between 90 to 1800 km^2, and mean elevations ranging from 4385 above mean sea level (amsl) to 4860 amsl. Seven years of irregularly sampled instantaneous streamflow measurements were available from these stream gauges (BGC 2019).

Climatologically, the project was located on the southern limit of the so-called Arid Diagonal, which separates the tropical zone of the Andes to the north, where the humidity comes from the tropical circulation, from the arid and semi-arid zone of the central Andes, where moisture results from winds coming from the west. This climate is characterized by low rainfall, low relative humidity, and high solar radiation.

Project Objectives

Integrated MWM is an essential component in mining and plays an important role in the decision-making process of the mining operation. Issues such as the availability of water supply, demand management, infrastructure design, and evaluation of water environmental and social impacts form a key element in a project strategy.

In this context, SRK was tasked with developing a conceptual and numerical model in GoldSim to simulate the watershed behaviour of the study area to evaluate the impact of the construction and operation of the project on the flows in the study area.

Six key objectives formed the basis for the models:

- Develop a climate model based on the historical records at the site that allows a stochastic generation of synthetic climatic variables of precipitation and temperature for use in the model.
- Incorporate climatic trends using long-term climate predictions. Notably, the cyclic El Niño Southern Oscillation (ENSO)

and Intergovernmental Panel on Climate Change (IPCC) climate change predictions were incorporated into the synthetic climate record.

- Establish a simulated baseline flow in the study area to compare against future projections.
- Evaluate the project impact both with and without climatic trends on streamflow in the study area.
- Evaluate the project from the pre-development stage for several decades into the post-closure period.
- Incorporate flexibility into the model to allow it to evaluate different mine plans and mining strategies for the same criteria during future studies.

Conceptual Model

The model was designed to include individual components developed separately, but incorporated into a single model so that the simulation would function as a single, integrated whole.

Climate Simulation

The climatic component of the model produced precipitation and temperatures representative of the historic climate at the site and incorporated both the effects of the El Niño La Niña cyclical effect and projected climate change over the multi-decade period the model was evaluated for.

Extension of Site Records

The local site information consisted of 5 to 6 years of historical records (BGC 2019). However, for the long-term trends needed for the precipitation-runoff models, decades of continuous information gathered from several external sources are required.

For this project, the site data were extended using various sources of satellite information, climatic gridded models, and hybrid satellite sources, combined with machine intelligence. After evaluating several sources, the Modern-Era Retrospective Analysis from Research and Applications, Version 2 (MERRA2) (NASA 2019) and European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis series number 5 (ERA-5) (ECMWF, 2019) data sources were selected as most relevant. MERRA2 included daily data from 1983 to current (2018 at the time of development) for the entire world, based on a 0.5° latitude by 0.5° longitude grid, while ERA-5 included sub-daily data from 1979 to current for the entire world, based on a 0.25° latitude by 0.25° longitude grid.

Statistical analysis produced a daily Pearson correlation of 0.97 between air temperature from the site stations with the MERRA2 gridded dataset. The two data sets also aligned with the adiabatic lapse rate (i.e., temperature vs. elevation) of approximately 5.7 °C per 1000 m. The local temperature records were patched and extended with a linear regression from the MERRA2 dataset.

For total precipitation, statistical analysis produced a monthly Pearson correlation of 0.7 to 0.9 between the local records and the ERA-5 dataset. Using this relationship, local records were patched and extended back to 1979. The daily local records were extended using quantile mapping (Gudmundsson et al. 2012), where the ERA-5 daily precipitation distribution was matched with the local distribution observed at the site.

These extension and patching methods provided site relevant daily records from 1980 to 2018 without any gaps for daily maximum and minimum air temperature and total precipitation.

Climate Oscillations

The El Niño La Niña cyclical effect, or El Niño Southern Oscillation (ENSO) is an ocean-atmosphere interaction that can cause weather cycles on a time scale of years to decades.

A statistical comparison of the monthly averages of the patched and extended site climate records were compared against the Multivariate ENSO index (MEI) (NOAA 2020), a measure of the strength of the historic ENSO effect from 1951 to 2018, typically in the range of -2 to +2.

The analyses indicated that there was no significant effect on temperature from the ENSO effect, but that the ENSO effect did produce a response in precipitation values. As can be seen in Figure 1, average rainfall was 20 mm to 30 mm greater during periods of positive MEI during the winter months of July and August.

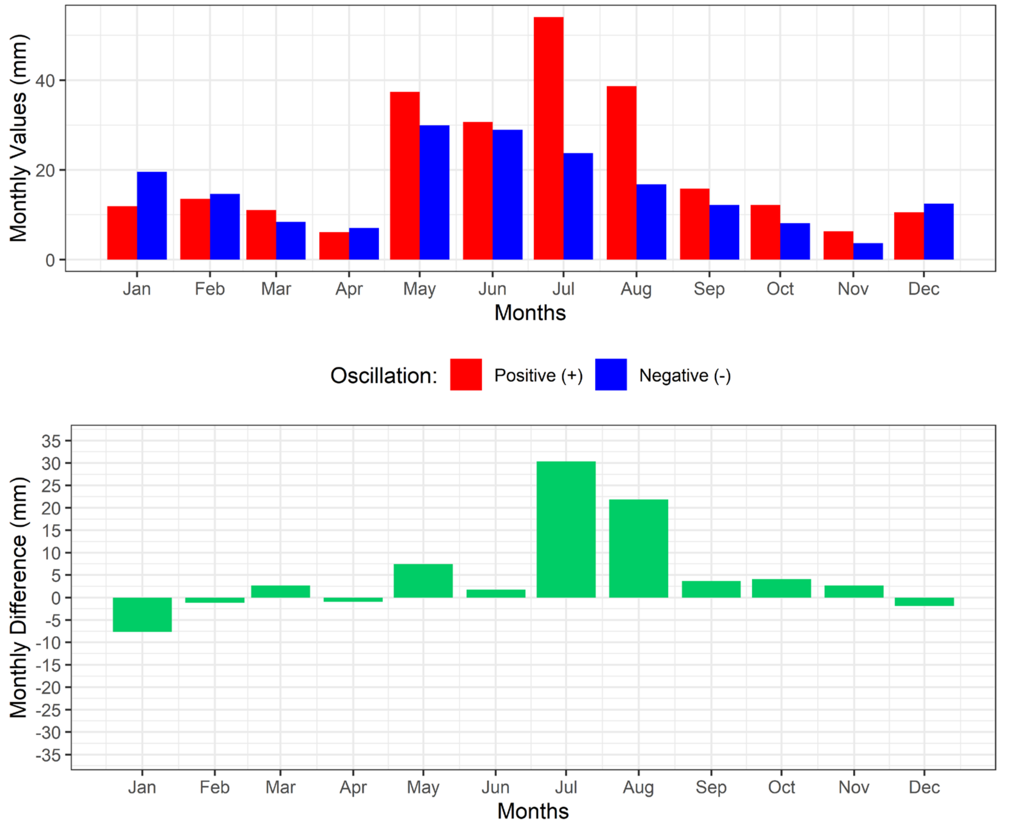

***Figure 1** Average monthly precipitation for years of positive and negative MEI*

***Table 1** Trends in climate change climate variables for the Project*

Period	Change from baseline [%]			Average		
	Precipitation Total (% change from baseline)	Maximum Temperature (% change from baseline ºK)	Minimum Temperature (% change from baseline ºK)	Precipitation Total (mm)	Maximum Temperature (ºC / ºK)	Minimum Temperature (ºC / ºK)
Baseline (1976-2005)	0	0.00	0.00	219	0.83 / 273.98	-0.93 / 272.22
2020s (2011-2040)	-11	0.43	0.37	194	2.02 / 275.17	0.08 / 273.23
2050s (2041-2070)	-22	0.80	0.74	171	3.02 / 276.17	1.08 / 274.23
2080s (2071-2100)	-27	1.15	1.10	160	3.98 / 277.13	2.06 / 275.21

Climate Change

SRK evaluated the effects of future climate on the Project using the IPCC Fifth Assessment Report (AR5) (IPCC 2014) and the information and models of the NASA Earth Exchange Global Daily Downscales Projections (NEX-GDDP) (Thrasher et al. 2012) to estimate the impacts on precipitation and temperature.

The climatic predictions were presented from 2011 to 2100, considered the maximum reasonable period to extend the predictions. Within this window, three, 30-year periods were applied to evaluate the change in precipitation and temperature from the baseline of 1976 to 2005. Each of the 26 models available in NEX-GDDP projections was evaluated and the median change for the RCP 4.5 climate scenario with respect to the baseline condition was selected, as shown in Table 1.

The climate change predictions predicted a decrease of annual precipitation in the region and an increase in temperature, which translated as an increase in winter rainfall at the expense of snowfall due to rising temperatures. Both effects would result in a smaller snowpack compared to the baseline, with a net effect of an earlier and shorter snow melt season.

Precipitation-Runoff Hydrological Model

The high complexity of the process of generating flows of the high mountain range (sublimation, snow capture efficiency, effect of glaciers, interaction with groundwater system, among others), as well as the limited flow records at the site, indicated the need for a model that simplifies unknown factors but is still representative of the basin hydrology.

An evaluation of available the rainfall-runoff models resulted in the selection of the GR5J “Modèle du Génie Rural à 5 paramètres Journalier“ (rural engineering of 5 daily parameters model) with the snow melt model CemaNeige (Le Moine 2008).

A flow schematic of the GR5J model (without the CemaNeige component) is shown in Figure 2. A total of five calibration parameters are used for each sub-watershed (labelled X1 through X5 in the Figure). An additional two parameters are used in the CemaNeige component to define the degree-day melt potential and thermal inertia in the snowpack.

Proof of Concept for Precipitation-Runoff model

Because of limited and sporadic flow records, calibration and validation of the local precipitation-runoff model was challenging. However, two downstream flow gauges operated by the national agency (San Juan Gobernment Argentina 2019) were used to validate the model.

Observed monthly flows from these regional gauges were used to calibrate the GR5J model, producing Nash Sutcliffe Efficiency

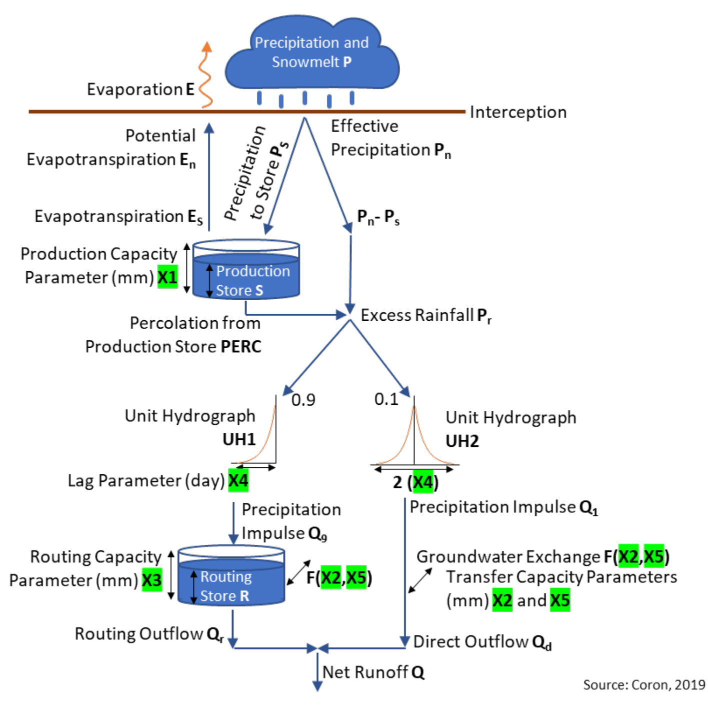

Figure 2 GR5J Schematic

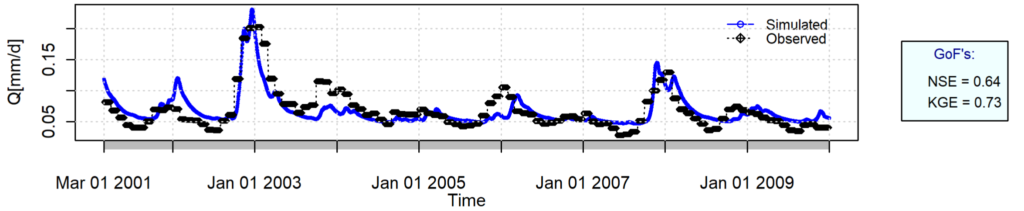

Figure 3 Daily comparison of simulated and observed runoff for the Regional Stream Gauge

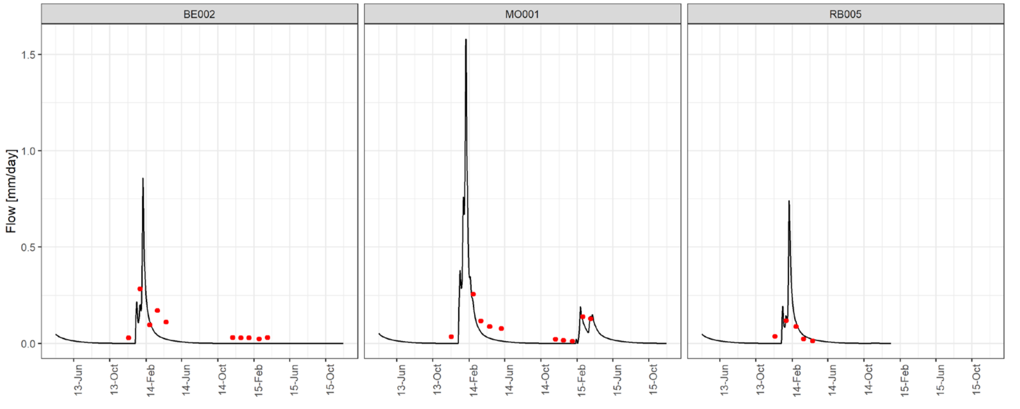

Figure 4 Comparison between GR5J model and measured flows

(Nash et al. 1970) and Kling-Gupta efficiency (Gupta et al. 2009) from 0.6 to 0.9, which suggest the model is representative and significant (Moriasi et al. 2007), as shown in Figure 3.

Local precipitation-runoff model

Starting with the calibration to the regional gauges, local records were calibrated based on performance similarities (runoff peak, location, and magnitude).

The calibration of the model was developed with historical records of on-site flow monthly between 2013 to 2015 as shown in Figure 4. Subsequent to the initial calibration efforts, climate inputs and flow records for the period of 2018–2019 were used to validate the 2013–2015 calibration.

Numerical Implementation

A single GoldSim (GTG 2018) numerical model was developed to integrate all the components of the hydrologic model.

The model used a synthetic climate generator based on the WGEN model (Richardson 1984) that synthetically generated daily precipitation and temperature. A custom module was developed that synthetically generated a MEI index, statistically based on the cycle length between peaks and magnitude of the historical MEI index. A correction factor to adjust precipitation from the magnitude of the MEI, based on the relationship between the MEI and site precipitation outlined in the climate oscillation discussion above, was applied to the WGEN output.

Similarly, the effects of climate change projections were applied to the ENSO-adjusted WGEN output using the correction factors based on the impact to precipitation and temperature for each 30-year climate period outlined in the climate change discussion above.

The climatic parameters were used as input to a GoldSim implementation of the CemaNeige model to produce rainfall, snowfall, and snowmelt, which was subsequently applied to an implementation of the GR5J model. This iteration transformed the rainfall and snowmelt into streamflow using the basin parameters developed for each watershed within the project area.

Results and Conclusion

The predicted modelling scenarios incorporated dynamic simulation of the mining activities in the basin, from pre-development through closure as shown in Table 2.

Table 2 Periods considered for the numerical model

Period	Start Year	End year
Pre-Development	1991	2019
Development	2021	2023
Operations	2024	2043
Closure/Post Closure	2044	2099

For the future projections, 100 realizations using a Monte-Carlo simulation of the stochastic climate generator simulated the system and produced streamflow within the basin in response to the loss of watershed from the mining activity, impact of the ENSO cycle, and effects of climate change. The simulation ran in parallel (i.e., subjected to the same climate conditions with no mining impacts) to provide a comparison of impacted and unimpacted conditions. See Figure 5 for an example of the impact for mining on the watershed.

In average terms, the synthetic climate generator produced precipitation totals similar to the historical record but with less variability. However, by including a correction factor for the impact of the ENSO effect, the standard deviation of precipitation records shows greater similarity to that observed historically.

The effect of climate change was observed in a 22% decrease in the average precipitation by 2070, while mean annual temperatures are predicted to increase approximately 2 °C for the same period. These changes generated a significant decrease in expected flows to the site due to the increase in evaporation losses, loss of spring freshet, and overall decrease in annual precipitation.

Streamflow results for the baseline scenario (with and without climate change effects) at control point RB008 are presented in Figure 6. The model predicted that, without climate change, summer flows could reach up to 2 m^3/sec, but by including the effect of climate change, they remained below 0.6 m^3/sec.

The main effect on the expected flows due to the project occurred in the PB001 basin where 65% of the basin area would be collected and used to supply the project water demands during the operational period of the project.

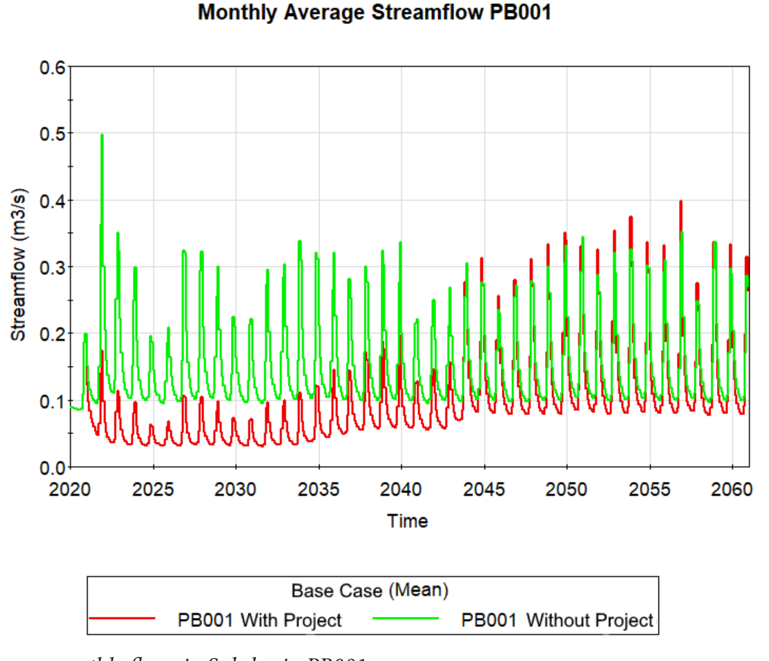

Figure 5 Average monthly flows in Sub-basin PB001

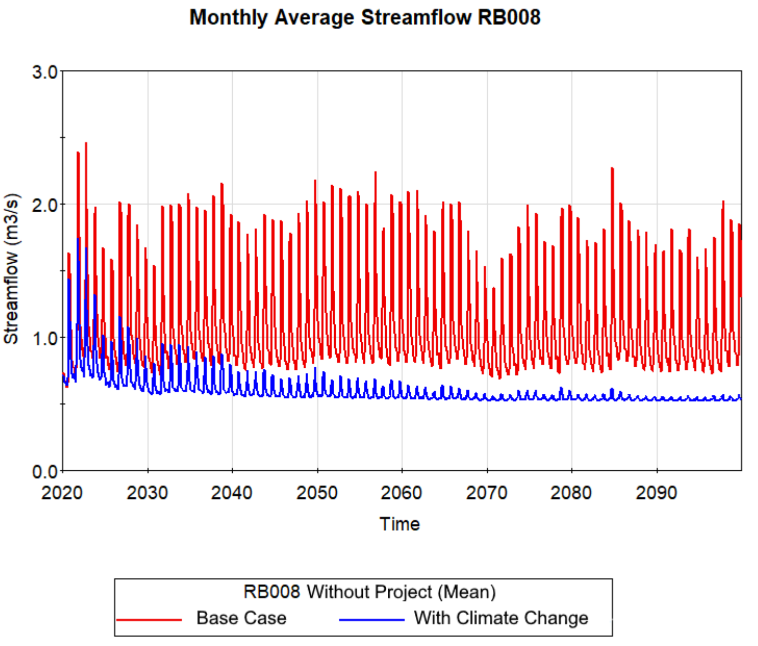

Figure 6 *Effect of climate change on monthly average flows at RB008*

For the closure and post-closure periods of the project, most of the watershed is returned to natural conditions. However, about 20% of the area of the PB001 basin would still be impacted by closed mine infrastructure and is predicted to produce less surface runoff than the natural condition.

At the farthest downstream extent of the Project, (RB008), there was no significant impact to the monthly average flows. During the operational phase of the project, the difference between average expected flows with and without the project was close to 3% of the average flow. During the post-closure period, the impact to the average flows did not exceed 2% even at the 5th and 95th percentile flow extremes because the area impacted by the closed facility was a very small percentage of the basin.

A comparison of the flow impacts from the mining activities during the post-closure period indicated that the loss of streamflow from climate change was significantly greater than that predicted by the post-closure changes to the watershed.

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